When It Rains, It Pours

Global Warming and the Increase in Extreme Precipitation from 1948 to 2011

ENVIRONMENT
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Executive Summary

Global warming is happening now and its effects are being felt in the United States and around the world. Among the expected consequences of global warming is an increase in the heaviest rain and snow storms, fueled by increased evaporation and the ability of a warmer atmosphere to hold more moisture.

An analysis of more than 80 million daily precipitation records from across the contiguous United States reveals that intense rainstorms and snowstorms have already become more frequent and more severe. **Extreme downpours are now happening 30 percent more often nationwide than in 1948. In other words, large rain or snowstorms that happened once every 12 months, on average, in the middle of the 20th century now happen every nine months. Moreover, the largest annual storms now produce 10 percent more precipitation, on average.**

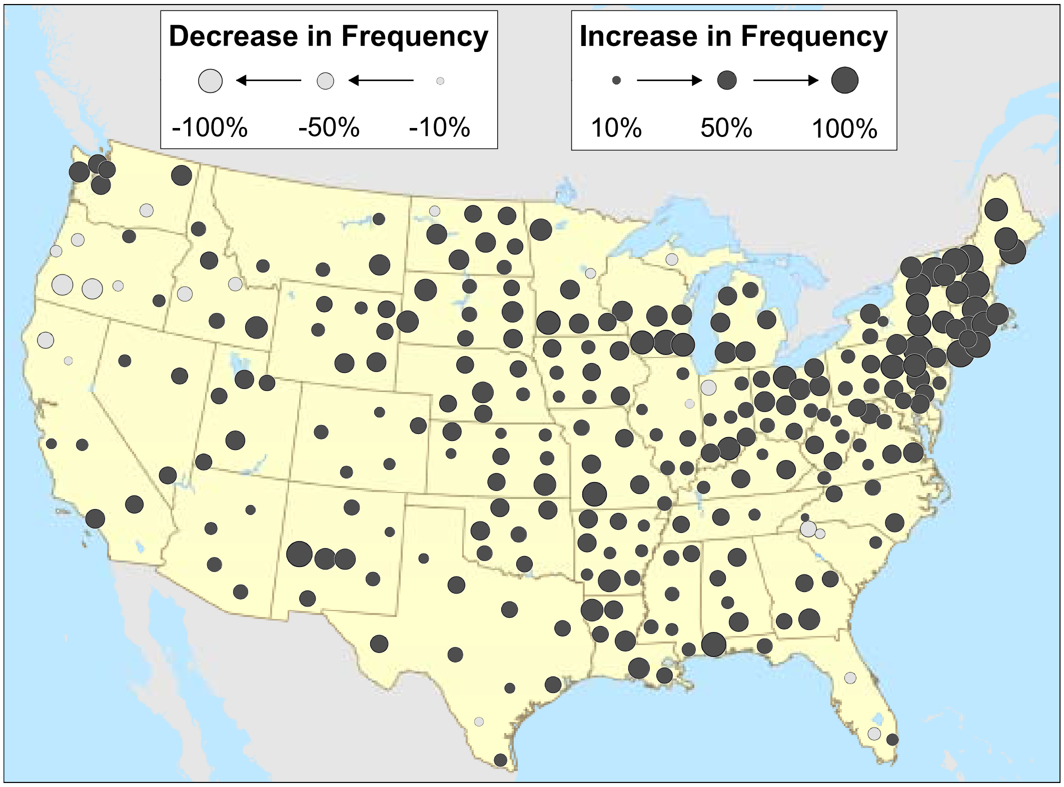
An increase in extreme downpours has costly ramifications for the United States, with the potential to cause more flooding that jeopardizes property and lives. With scientists predicting even greater increases in extreme precipitation in the years ahead, the United States and the world must take action to reduce pollution that contributes to global warming.

Extreme rainstorms and snowstorms are happening more frequently.

- Extreme downpours—rainstorms and snowfalls that are among the largest experienced at a particular location[#] —are now happening 30 percent more often on average across the contiguous United States than in 1948. (Our analysis covered the period from 1948 to 2011, which offered the most complete weather data.)
- New England has experienced the greatest change, with intense rainstorms and snowstorms now

[#]Specifically, we defined extreme events as those expected to occur no more than once per year on average at a particular location based on the historical record. In other words, we identified the 64 events at each weather station with the largest 24-hour precipitation totals across the 64-year time period of the study, and labeled them extreme.

Figure ES-1: Extreme Downpours Have Become More Frequent Across Much of the United States



happening 85 percent more often than in 1948. The frequency of intense rain or snowstorms nearly doubled in Vermont and Rhode Island, and more than doubled in New Hampshire. (See Figure ES-1.)

- The change has also been pronounced in the Mid-Atlantic, the South, the Midwest and the Mountain West. New York, Pennsylvania and Missouri each experienced an increase in extreme downpour frequency of more than 50 percent.

- In total, 43 states showed significant* increases in the frequency of extreme downpours. Only one state, Oregon, experienced a significant decrease. (See Table A-2 on page 34 for full data by state.)

The biggest rainstorms and snowstorms are getting bigger.

- Not only are extreme downpours more frequent, but they are also more intense. The total amount of precipitation produced by the largest storm

*The term "significant" here indicates a very high probability that the trend is real and not simply the result of chance, based on statistical analysis. Specifically, significant results showed 95 percent or greater probability that the slope of a best-fit line through the data was greater than zero, supporting the conclusion that the frequency of extreme downpours has increased.

in each year at each station increased by 10 percent over the period of analysis, on average across the contiguous United States.

- This trend was most pronounced in New England and the Middle Atlantic. Connecticut, Delaware, Massachusetts, Maine, New Hampshire, New Jersey, New York, Pennsylvania and Vermont all saw the intensity of the largest storm each year increase by 20 percent or more.

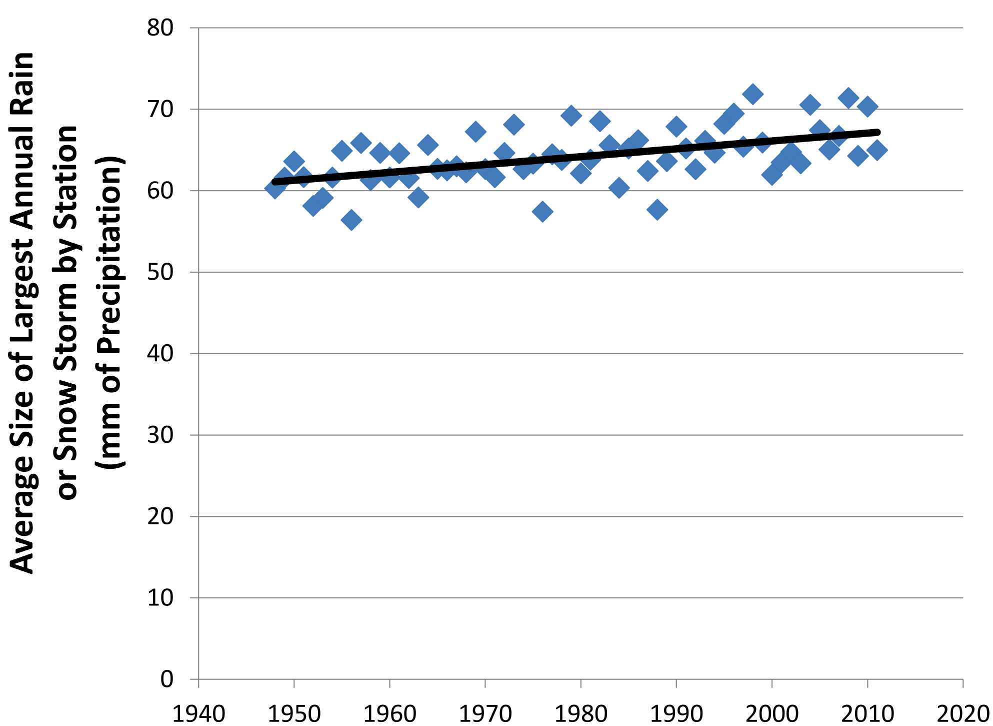
- The trend also occurred across the Midwest, the South and the West. In total, 43 states experienced a statistically significant increase in the amount of precipitation produced by the largest annual rain or snow storm. Only one, Oregon, recorded a significant decrease. For full state data, see Table A-4 on page 36.

Global warming—driven by pollution from the combustion of fossil fuels—is helping to fuel the increasing severity of downpours.

- The U.S. Global Change Research Program—composed of a wide range of leading experts from the U.S. National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, and universities—called the increase in heavy downpours "one of the clearest precipitation trends in the United States" and linked the phenomenon to global warming in its report, *Global Climate Change Impacts in the United States.*

- The average temperature in the United States has increased by 2° F over the last 50 years. Nine of the ten warmest years on record have occurred since 2000.

Figure ES-2: The Biggest Storms Are Getting Bigger



- Warmer temperatures increase evaporation and enable the air to hold more water. Scientists have found that the water content of the atmosphere is now increasing at a rate of about 1.3 percent per decade. The additional moisture loaded into the atmosphere by global warming provides more fuel for intense rainstorms and snowstorms.

Global warming will very likely drive future increases in extreme downpours, with a wide range of harmful consequences.

- Experts at the U.S. Global Change Research Program project that heavy downpours are very likely to become more frequent and more intense with further warming. "Heavy downpours that are now 1-in-20 year occurrences are projected to occur about every 4 to 15 years by the end of this century," according to their report, while producing 10 to 25 percent more precipitation per storm, depending on location and on the scale of future emissions of global warming pollution.

Flooding triggered by extreme downpours jeopardizes property and lives. In this photo, an SUV lies submerged in downtown Nashville, Tennessee, after a massive rainstorm in May 2010 triggered a 1,000-year flood through the city. Credit: Wayne Hsieh

- Extreme rain and snowstorms can harm people and property—primarily by increasing the risk of flooding. In 2011, floods killed more than 100 people and caused more than $8 billion in damage to property and crops.

- Bigger and heavier rainstorms and snowstorms will not necessarily lead to more water being available for ecosystems or human use. Indeed, scientists warn that some areas of the country may experience both heavier extreme rainstorms and more frequent and severe drought, due to higher evaporation of soil moisture and longer dry spells between significant rainstorms.

To protect our communities, our safety, and our environment, we must rapidly and substantially reduce pollution that causes global warming.

- Federal and state governments should **adopt and implement limits on global warming pollution** capable of reducing emissions to at least 35 percent below 2005 levels by 2020 and by at least 85 percent by 2050. These emission reductions are broadly consistent with what science tells us is necessary to lessen the most costly and devastating consequences of global warming.

- Short of economy-wide limits on global warming pollution, local, state and federal governments should **focus on reducing pollution from**

the largest sources—most notably power plants and transportation. The Obama administration's proposed carbon pollution standards for new power plants and the proposed carbon pollution and fuel efficiency standards for cars and light trucks through model year 2025 are two noteworthy proposals at the federal level. Regional programs such as the Northeast's Regional Greenhouse Gas Initiative can also help to achieve this goal.

- The United States—including federal, state and local governments—should adopt clean energy solutions that reduce our dependence on fossil fuels and emissions of global warming pollution. Among the most important steps are:

    - Adopting enforceable targets, financial incentives, regulatory changes and investment strategies that increase the use of **renewable energy** sources such as wind and solar power.

    - Implementing appliance standards, building codes, enforceable efficiency targets for utilities, fuel-efficiency standards for vehicles and other steps to promote **energy efficiency**.

    - Continuing to develop and implement the **fuels and technologies of the future—**from electric vehicles to energy storage devices to "smart grid" technologies and new renewable sources of energy—through government support of research, development and deployment of those technologies and the adoption of technology-forcing standards where appropriate.

- Federal, state and local officials should take steps to better **protect the public from the consequences of extreme weather events—**steps that save costs compared to suffering the full brunt of these extreme events. Government officials should explicitly factor the potential for global warming-induced changes in extreme weather patterns into the design of public infrastructure and revise policies that encourage construction in areas likely to be at risk of flooding in a warming climate.

Introduction

In mid-June 2012, a massive downpour flooded Duluth, Minnesota, breaking all-time rain records. Water levels in the St. Louis River jumped 5 feet, reaching record high flood stage. The deluge destroyed roads across the region, and flooded two-thirds of the city zoo, killing all of the barnyard animals.[1]

A week later, a massive tropical depression dropped more than 25 inches of rain on parts of Florida, impacting hundreds of thousands of people, many of whom were forced to evacuate flooded homes.[2]

In Nashville, 14 inches of rain fell over two days in May 2010—more than twice as much as had ever fallen in a two-day span in the city's recorded history. The event triggered a "1,000 year" flood, inundating the Country Music Hall of Fame, inflicting nearly $2 billion in damage, and killing 30 people.[3]

In Chicago, more than 1,500 vehicles and their occupants were stranded along Lake Shore Drive in February 2011 as the city experienced its third-largest snowfall in recorded history—part of a massive winter storm that blanketed much of the nation in snow and ice.

In Louisiana, federal officials were forced to open the gates of the Morganza Spillway in 2011 for the first time in nearly four decades to alleviate flooding. By opening the floodgates, officials were able to prevent damaging flooding in Baton Rouge and New Orleans, but only at the expense of flooding 100,000 acres of farmland. Ironically, the flooding—caused by intense precipitation upstream in the Ohio River valley—came at a time when Louisiana itself was experiencing a drought.

In the Upper Plains, May 2011 saw the Missouri River reach flood stage in every state through which it passed, inundating 450 square miles of farmland, closing every bridge over the Missouri along a 100-mile length of the river, and flooding the grounds of Nebraska's Fort Calhoun nuclear power plant. In North Dakota, the Souris River overwhelmed flood defenses designed to withstand a 100-year flood, damaging 4,000 homes and forcing cancellation of the state fair.

In Binghamton, New York, the city recorded its second "100-year" rainfall in two years in September 2011, sending the Susquehanna River to a record-high flood level and inundating the city's downtown for the second time in five years.

These examples of extreme rainfall may seem like isolated incidents, but they are part of a larger story connected to global warming. Scientists have concluded that "global warming is unequivocal and primarily human-induced," mainly caused by the emissions of heat-trapping gases from activities such as the combustion of fossil fuels.[4]

Global warming is increasing the frequency and/or severity of some types of extreme weather. The impacts of warming are being felt now. And they are harming our communities, jeopardizing our safety, and threatening our environment in tangible ways.

In this report, we analyze the precipitation records of thousands of weather stations across the country over the last six decades. We find that the largest rainstorms and snowstorms are happening more frequently and producing larger amounts of precipitation.

In other words, increasingly, when it rains, it pours.

Given the changes that humanity has already made to the atmosphere, some future impacts are now unavoidable. But how much worse it will get is largely within our control. If we continue to burn more fossil fuels each year, the planet will become much warmer and extreme precipitation will become much more common and intense. But if we reduce our emissions of the pollution that drives global warming, we can limit the risk of increasingly extreme weather.

Achieving the cuts in emissions needed to prevent the most dangerous impacts of global warming won't be easy, but it can be done if we act now. By establishing ambitious goals for reducing pollution—and using energy efficiency and clean, renewable energy to meet them—we can stave off the worst effects of global warming.

In Nashville, 14 inches of rain fell over two days in May 2010—more than twice as much as had ever fallen in a two-day span in the city's recorded history. The event triggered a "1,000 year" flood, inflicting nearly $2 billion in damage, and killing 30 people. The event is part of a larger story connected to global warming, which is increasing the frequency and/or severity of some types of extreme weather, including extreme downpours. Credit: David Fine, FEMA

Global Warming Is Providing More Fuel for Rainstorms and Snowstorms

Global warming is happening now. The average temperature in the United States has climbed more than 2° F over the past 50 years.[5] Nine of the ten warmest years on record have occurred since 2000. The warmest year on record occurred in 2010; 2011 was the ninth warmest.[6] July 2011 to June 2012 was the warmest 12-month period the contiguous United States has experienced since record-keeping began in 1895.[7] The most trusted authorities on the subject—including the National Oceanic and Atmospheric Administration, the U.S. National Academy of Sciences and the Intergovernmental Panel on Climate Change—attribute the warming primarily to human-induced emissions of heat-trapping gases, including pollution from the combustion of coal, gasoline and other fossil fuels.[8]

Warming is already having an impact. Among the predicted effects of global warming is an increase in heavy rain and snow storms, fueled by increased evaporation and the ability of a warmer atmosphere to hold more moisture. In fact, scientists have observed increases in extreme precipitation in many locations across the world.

Warming Increases Evaporation and Enables the Air to Hold More Water Vapor

Warmer temperatures cause more evaporation, and warmer air holds more water, intensifying the water cycle. (See Figure 1.)

Just as water dries from the ground when the sun comes out after a storm, increased temperatures accelerate the rate at which moisture evaporates from the ocean surface, from soil, from plants, and from inland water bodies.

Warmer air can hold more water once it has evaporated. The water-holding capacity of the air increases roughly exponentially with temperature. Using satellites and ground-based measurements, scientists have found that the water content of the atmosphere is now increasing at a rate of about 1.3 percent per decade, consistent with expected changes given the temperature increases that have occurred.[10]

Scientists have linked the increase in atmospheric water content to global

warming, driven by emissions of heat-trapping pollution.[11]

This excess moisture provides more fuel for intense downpours—and more intense snowstorms at times and in places where it is cold enough to snow.

Fueled by Extra Water Vapor, Patterns of Extreme Precipitation Are Changing Around the World

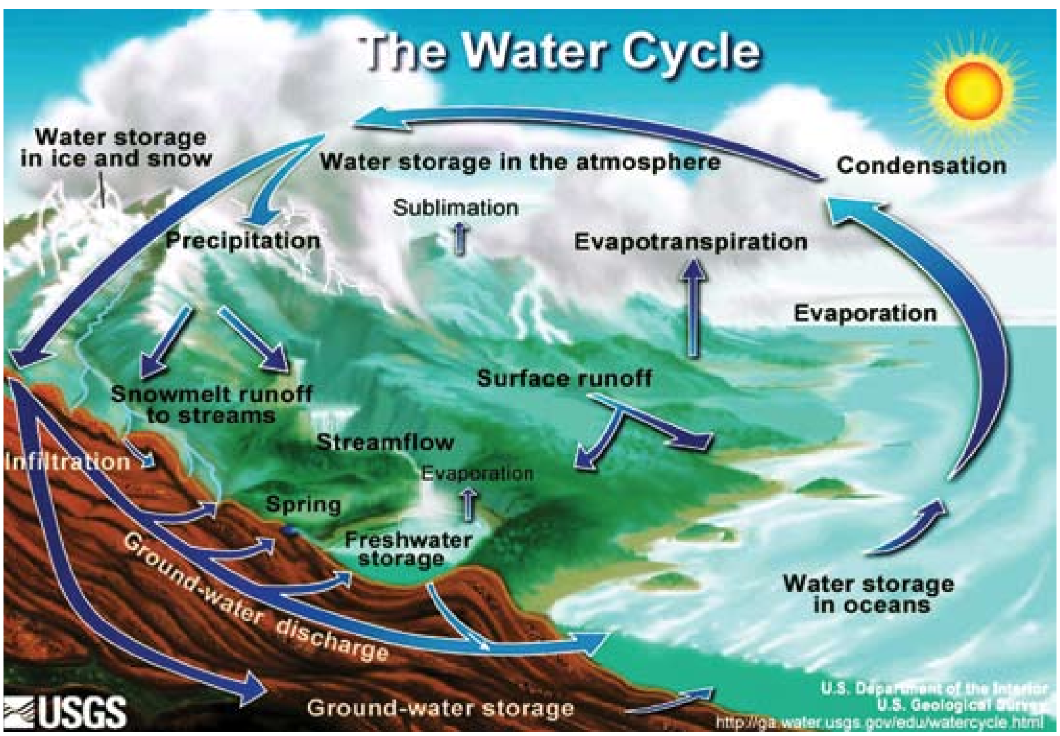
As the saying goes, "what goes up must come down." Consistent with the fact that warming has loaded more water into the atmosphere, scientists have observed increases in heavy precipitation frequency and intensity in many locations across the world, although the trend varies across regions and seasons.

In the language of the Intergovernmental Panel on Climate Change, "it is likely that there have been … significant increases in the number of heavy precipitation events in more regions than there have been … significant decreases, but there are strong regional and subregional variations in the trends."[14]

North America

The strongest evidence of the increasing frequency of heavy precipitation events comes from North America, particularly the mid-latitudes of the United States. In the words of the U.S. Global Change Research Program, which has made the world's largest scientific investment in

Figure 1: Warming Intensifies the Water Cycle



Global warming intensifies the water cycle. Increased temperatures drive faster evaporation and allow the atmosphere to store more water vapor, allowing clouds to become richer in moisture and fueling an increase in the frequency and intensity of the biggest rain and snow storms. The water content of the atmosphere is now increasing at a rate of about 1.3 percent per decade, consistent with expected changes given the temperature increases that have occurred.[12] Credit: United States Geological Survey

Expressing Confidence in the Conclusions of Climate Science

Climate scientists use plain-language terms with specific meanings to express the level of confidence in their conclusions about how our climate is now changing and will change in the future. Generally, a "likely" conclusion has at least a two-thirds probability of being correct given available evidence, and a "very likely" conclusion has at least a 90 percent chance of being correct. When no specific quantitative probability of the accuracy of a conclusion is available, scientists choose qualitative expressions of high, medium or low confidence based on the type, amount, quality, and consistency of evidence available, as evaluated in synthesis reports such as *Global Climate Change Impacts in the United States* and the works of the Intergovernmental Panel on Climate Change, the world's leading scientific authority on global warming.[9] This report relies on these authoritative sources when discussing scientific literature addressing past and projected impacts of global warming, using these same plain-language terms to relay scientists' confidence in the conclusions of current climate science.

global warming research, the increasing frequency and intensity of heavy downpours is "[o]ne of the clearest precipitation trends in the United States."[15] Climate scientists have observed that:

- Extreme downpours have become more common over the last half century in North America, at the same time that overall precipitation has slightly increased.[16] In the United States, the biggest storms have gotten bigger. Average annual precipitation increased by about 7 percent over the past century, while the amount of precipitation falling in the heaviest 1 percent of rain events increased nearly 20 percent.[17]
- The average amount of rain falling on days with rainfall has increased over Canada, the United States and Mexico.[18]
- Extreme downpours became about 20 percent more frequent between 1950 and 2007 across the contiguous United States.[19] Greater areas of land have become exposed to above-normal heavy downpours.[20]

Global Warming Can Make Snowstorms Bigger Too

Whether precipitation falls as rain or snow is a function of the air temperature near the ground. The same conditions that have led to more intense rainstorms in our warming world—including increased evaporation and the ability of warmer air to hold more water vapor—can also be expected to contribute to an increase in extreme snowstorms in places where it remains cold enough to snow. Indeed, a study of snowstorms during the 20th century found that most snowstorms occurred during *warmer*-than-normal years in most of the United States.[13]

Flooding triggered by extreme downpours can be deadly, especially when floodwaters overtake vehicles. The occupants of this vehicle were rescued after flooding from heavy rainfall washed the car off of the highway near Kingfisher, Oklahoma, in August 2007. Credit: Marvin Nauman, FEMA

- The largest downpours have become more intense, especially toward the end of the 20th century.[21]

- While statistically significant increases in extreme precipitation appeared in many locations, some small regions—such as coastal stations in Mexico—either did not have such a trend, or the data record was insufficient to detect a trend.[22]

Recent science links the observed increase in extreme downpours over much of the land area of the Northern Hemisphere to human emissions of heat-trapping pollution.[23] The Intergovernmental Panel on Climate Change—the world's leading scientific authority on climate change—expresses "medium confidence" that this conclusion also applies at the global scale.[24]

Extreme Precipitation Poses a Threat to Our Society

Extreme rain and snow storms can damage or destroy buildings and property, wipe out crops, disrupt transportation systems, and—in some cases—severely injure or kill people.

Floods are a particularly damaging consequence of extreme rain and snowstorms. Heavy precipitation is only one factor in the incidence of damaging floods, but it is an important one. Whether a heavy storm leads to flooding also depends on the timing of extreme events, where the storm occurs, and the effectiveness of human-built systems in managing stormwater runoff.

During the 20th century, floods caused more property damage and loss of life than any other type of natural disaster in the United States.[25] Flood damages often exceed a billion dollars per year.[26]

Death and Injury

During 2011, flooding killed 113 people in the United States—about 20 more than during a typical year.[27] Almost two-thirds of those killed were trapped in their vehicles when overtaken by floodwaters.[28]

Flooding triggered by an extreme downpour can be particularly deadly, as tragically demonstrated by the massive amounts of rainfall unleashed by Hurricane Irene in August 2011. In northern New Jersey, several rivers hit record levels, causing major damage to more than 2,000 homes.[29] Irene's rains easily placed August 2011 as the wettest month in New Jersey since at least 1895—surpassing the previous monthly record for rainfall by nearly 40 percent.[30] In Vermont, the flooding caused by Irene's intense rains was one of the state's worst natural disasters since 1900.[31] Parts of Vermont received up to 11 inches of rain.[32] Rain falling on already saturated soil in the mountain areas caused roaring flash floods, and rivers in parts of Vermont surpassed their record flood levels, some of them by several feet.[33] Residents of 13 towns were temporarily cut off from the outside world as roads and bridges were washed away.[34] Throughout the East, 45 people died as a result of the storm.[35]

Infrastructure and Property Damage

Flooding triggered by extreme downpours can wash out roads and bridges, inundate homes and businesses, disrupt transportation, and cause widespread economic disruption.

For example, one particularly massive downpour hit Nashville, Tennessee, on May 1 and 2, 2010. The storm unleashed 13.57 inches of rainfall—more than double the previous two-day record and enough to make the first two days of May alone wetter than any other May on record.[36] The storm broke roughly 200 daily, monthly and all-time precipitation records across Tennessee and neighboring states.[37] Property damage from the flood—which achieved "1,000-year flood" status across a broad swath of Tennessee—exceeded $1.5 billion.[38] Floodwaters inundated much of Nashville, including landmarks such as the Country Music Hall of Fame and LP Field, the home of the NFL's Tennessee Titans.[39]

The massive flooding along the Missouri River in June 2011—fueled by snowmelt and runoff from an unusually large number of extreme storms in the watershed that spring—caused massive infrastructure damage. At one point in the year, the Missouri River was in flood stage in every state through which it passed.[40] The flooding river caused several levees to give way and inflicted as much as $1 billion worth of damage to the region's flood control system.[41] During part of June, all bridges across the Missouri along a 100-mile stretch of the river were closed due to flooding. Floodwaters "virtually obliterated" several miles of Interstate 680 between Council Bluffs, Iowa, and Omaha, Nebraska, and damaged many other major and minor roads.[42] Floodwaters invaded the site of the Fort Calhoun nuclear power plant, which regulators anticipate will remain offline until fall 2012 due to the need for extensive inspections and repairs.[43]

Overall in 2011, flooding caused $8 billion in property damage.[44]

Crop Damage

Extreme downpours can directly damage farm crops, or cause flooding that wipes out whole harvests.

Heavy precipitation can saturate soils with moisture, creating conditions low in oxygen that directly damage crops and increase the risk of disease and insect infestation. Heavy precipitation can also interfere with planting, harvesting or other production steps that require the operation of machinery.

For example, the massive 1993 flood along the Mississippi River caused $6 to $8 billion in damage to farmers.[45] More than

two-thirds of total crop losses were due to supersaturated soils from heavy rains as opposed to floodwater submersion.[46] In Iowa in the 1980s and 1990s, damage from excess soil moisture was five times larger than direct damage from flooding.[47]

Floods triggered by extreme precipitation can also submerge farm fields and destroy crops. Massive flooding along the Missouri River in June 2011, for example, damaged approximately 450 square miles of farmland.[48] Farmers in western Iowa alone lost more than $200 million of their annual harvest.[49]

A research team led by Cynthia Rosenzweig at the NASA-Goddard Institute for Space Studies and Columbia University found that from 1951 to 1990, heavy precipitation caused an average of $3 billion per year in damage to the U.S. corn crop.[50] Moreover, the team estimated that the trend toward increasingly frequent extreme precipitation could double losses in U.S. corn production from heavy precipitation by 2030.[51]

Water Pollution

Extreme downpours create massive amounts of runoff. This runoff can increase sedimentation in rivers and overwhelm sewage infrastructure, increasing water pollution.

For example, in March 2010, New England was struck by a series of "Nor'easters" that dumped record rainfall on the region. On March 13, a large storm dropped 6 to 10 inches of rain in parts of New England and the mid-Atlantic region. Then, two weeks later, a second major storm deposited several more inches of rain on the region's already saturated ground. Rainfall records throughout the region were smashed, with

In June 2011, massive flooding along the Missouri River—fueled by snowmelt and runoff from an unusually large number of extreme storms in the watershed that spring—inflicted as much as $1 billion worth of damage to the region's flood control system and inundated several miles of Interstate 680, including the intersection of I-29 and I-680 by Mormon Bridge in Council Bluffs, Iowa (pictured here). Credit: U.S. Army Corps of Engineers

New York, Boston and Portland, Maine, experiencing their rainiest March ever and Providence setting a record for its all-time rainiest month since records have been kept.[52] The Pawtuxet River in Rhode Island crested at nearly 21 feet—12 feet higher than its usual level—leaving homes, businesses and transportation infrastructure underwater.[53] The massive runoff overwhelmed and damaged sewage treatment plants, creating an environmental crisis as raw sewage flowed into Narragansett Bay.[54]

A study conducted in 2001 found that just more than half of all waterborne disease outbreaks in the United States happened after a storm ranked in the top 10 percent by precipitation total.[55] The Union of Concerned Scientists reviewed many of the health risks that follow flood events in a 2012 report.[56]

The Frequency and Severity of Heavy Downpours Are Increasing Across the United States

Global warming is making extreme downpours more frequent and more severe across much of the United States.

In this report, we evaluate how global warming is now changing the frequency and intensity of storms with extreme levels of precipitation. We analyzed daily precipitation records spanning from 1948 through 2011 at more than 3,700 weather stations across 48 states, comprising more than 80 million records. At each individual weather station, we identified the 64 storm events with the largest 24-hour precipitation totals (including both rain and snow) across the 64-year time period. This definition of extreme precipitation is relative to the local climate at a given weather station, focusing on storms expected to occur no more than once per year on average at any particular location based on the historical record. (For a more detailed explanation of the methodology, see page 30.)

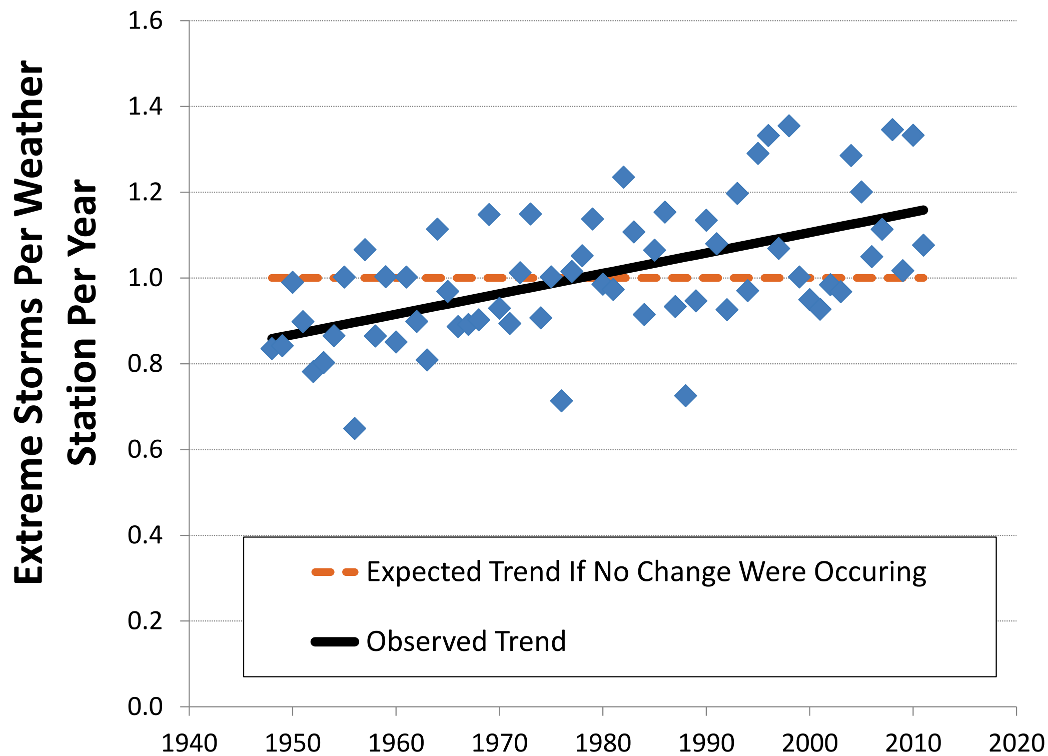
We found that extreme downpours increased in frequency by 30 percent from 1948 to 2011. In other words, heavy rain or snow storms that occurred an average of once every 12 months in the middle of the 20th century now happen every nine months on average. Moreover, the largest annual storms produced 10 percent more precipitation, on average, in 2011 than in 1948. These conclusions are consistent with earlier observations by climate scientists and with the anticipated impacts of global warming.

Extreme Downpours Are Happening More Frequently

Over the past six decades across the contiguous United States, the most intense rain and snowstorms have become 30 percent more frequent.

Figure 2 presents the average annual frequency of such storms across the United States from 1948 to 2011. The horizontal dashed line at "1" — representing an average of one extreme storm per year at each weather station — shows what the trend would be expected to look like if no change were occurring. However, the actual trend, represented by the solid line, is increasing. This trend is highly significant—meaning that it is very likely that the increase is a

Figure 2: Extreme Rain and Snow Storms Have Become More Frequent



real phenomenon rather than a random anomaly, based on statistical analysis. With 95 percent confidence,* the average increase in extreme precipitation frequency across the United States over the last 64 years lies between 29 and 31 percent.

The top five years with the largest number of extreme precipitation events, relative to the local climate at each weather station, have all been in the last 15 years. On average across the 48 contiguous states, 2008, 1996, 1998, 2010 and 2004 showed the greatest number of storms with extreme levels of precipitation.

New England Experienced the Largest Increase in Extreme Downpour Frequency

In New England, extreme downpours and snowstorms have become 85 percent more frequent over the last six decades, leading all regions. In other words, heavy rain or snow storms that, on average, recurred once every 12 months in the region in the middle of the 20th century now happen every 6.5 months, on average. The trend toward increasingly frequent downpours is also pronounced in the Mid-Atlantic, the

*Confidence levels represent the range of values in which the actual trend probably lies. The narrow range suggests that it is highly probable that the trend toward the increasing frequency of extreme downpours in the contiguous United States is real, and not simply a matter of random chance, and that it has been roughly of this magnitude.

South (including the South Atlantic, the West South Central and the East South Central regions), the Midwest (including the West North Central and East North Central regions), the Mountain West, and the Pacific. (See Table 1 and Figure 3.)

At the state level, 43 states showed statistically significant increases in the frequency of extreme storms.

The trend was particularly pronounced across New England. The frequency of extreme rain or snow storms more than doubled in New Hampshire, with storms that once occurred every 12 months, on average, now occurring every 5 to 6 months, on average. Massachusetts, Rhode Island and Vermont experienced an increase in extreme rainstorm or snowstorm frequency of more than 80 percent. Other states in New England—Connecticut and Maine—showed an increase in extreme storm frequency of more than 70 percent.

In the Mid-Atlantic, both New York and Pennsylvania experienced an increase in extreme storm frequency of more than 50 percent. In the Midwest, Ohio, Missouri and South Dakota also showed an increase in extreme downpour frequency of close to 50 percent. In the South, Alabama and Louisiana experienced an increase of more than 40 percent.

Four states either experienced no trend, or did not have enough data to conclusively detect a trend—Delaware, Florida, Maryland, and South Carolina. Only one state, Oregon, experienced a significant decrease in extreme precipitation frequency.

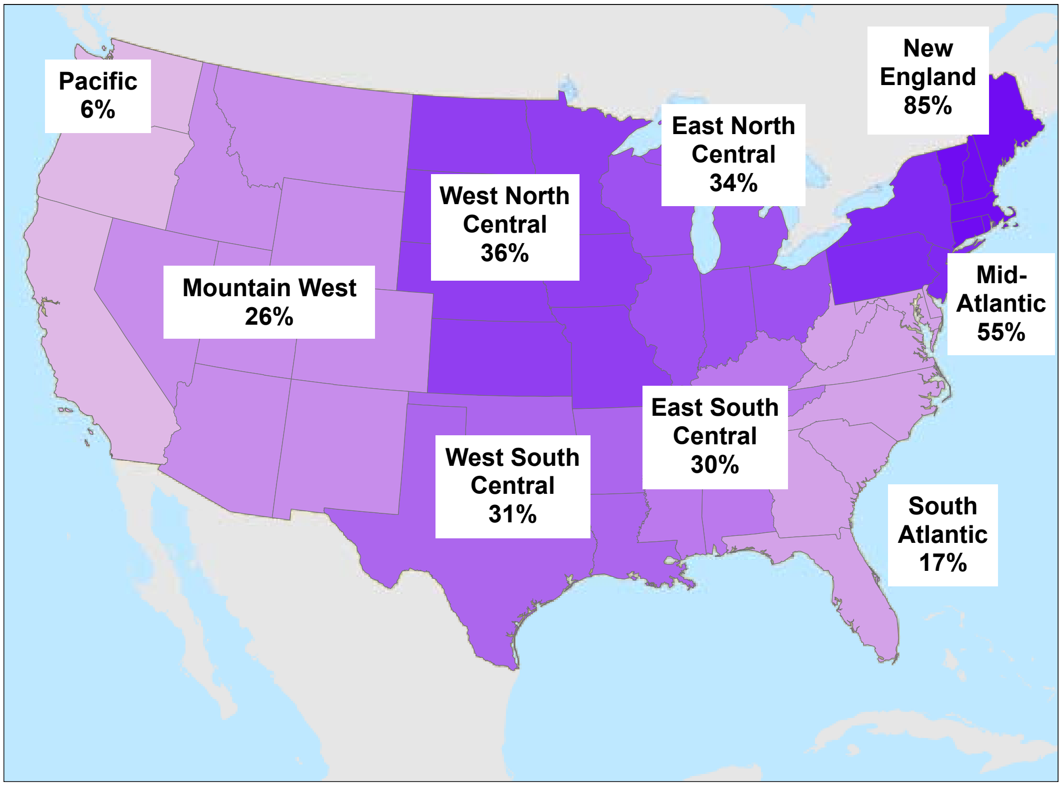
For a full list of extreme downpour fre-

Table 1: Regional Trends in Extreme Rainstorm and Snowstorm Frequency

Region	Increase, in Frequency, 1948-2011	A Storm That Used to Occur Every 12 Months Now Occurs on Average Every:	Is the Trend Significant?*
New England	85%	6.5 months	Yes
Middle Atlantic	55%	7.7 months	Yes
West North Central	36%	8.8 months	Yes
East North Central	34%	9.0 months	Yes
West South Central	31%	9.1 months	Yes
East South Central	30%	9.2 months	Yes
Mountain West	26%	9.5 months	Yes
South Atlantic	17%	10.3 months	Yes
Pacific	6%	11.3 months	Yes
Oregon plus California North of San Francisco Bay	-25%	16.0 months	Yes
California South of San Francisco Bay	35%	8.9 months	Yes

*The term "significant" here indicates a very high probability that the trend is real and not simply the result of chance, based on statistical analysis. Specifically, significant results showed 95 percent or greater odds that the slope of a best-fit line through the data was greater than zero, supporting the conclusion that the frequency of extreme downpours has increased. See Table A-1 on page 34 for more detailed results including the 95 percent confidence interval.

Figure 3: Regional Trends Toward Increased Extreme Rainstorm and Snowstorm Frequency



quency trend data by state, see Table A-2 on page 34.

We also investigated whether the trend could be traced to finer levels of geography. Trends are more difficult to ascertain within smaller regions, because extreme events by their nature are inherently rare and subject to natural random variability, and smaller areas tend to have fewer weather stations and thus less available weather data to capture extreme storms. (For example, this study includes data from 290 weather stations in Texas, but only three stations in Delaware, a much smaller state.) As a result, trends at narrower levels of geographic focus tend to be much less easy to detect and less precise than those covering larger areas and including more weather stations.

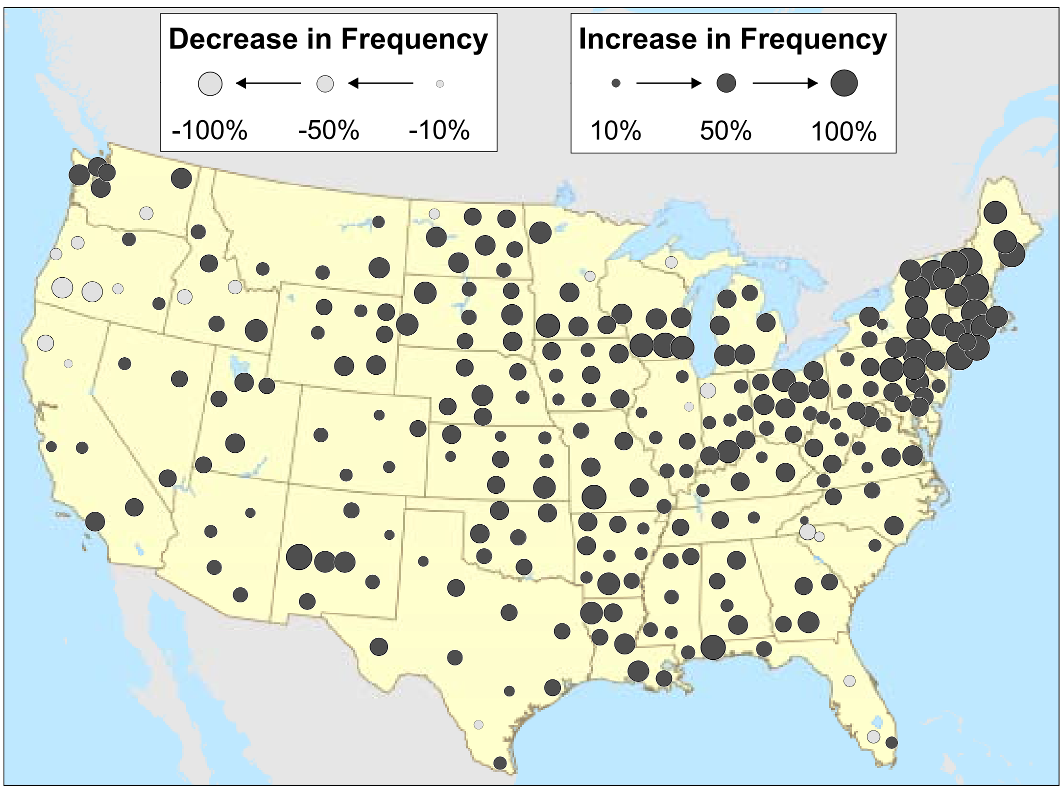
Since the 1950s, meteorologists have used climate divisions as a rough way to group weather measurements within states. Climate divisions group the country into 344 regions, with up to 10 divisions per state.[57] Figure 4 presents the trend in frequency of storms with heavy precipitation by climate division from 1948 through 2011. Apparent increases—at greater than 68 percent confidence—occurred in climate divisions covering 72 percent of the area of the contiguous United States.[58] (See the dark circles). In contrast, apparent decreases occurred in climate divisions covering about 7 percent of national land area. (See the light circles.) The remainder of the climate divisions either did not display a local trend, or did not have enough data to detect any local trends.

The Biggest Storms Are Getting Bigger

At the same time that extreme downpours have become more frequent, the amount of rain or snow those storms produce in each year has been increasing. The biggest storms in 2011 produced about 10 percent more precipitation than the biggest storms in 1948.

We looked at the amount of precipitation falling in the largest 24-hour precipitation event recorded at each weather station in each year, choosing one storm per year at each station. The total amount of precipitation from these storms increased 10 percent over the period of analysis, aggregated across the contiguous United States. (See Figure 5.) This trend was most pronounced in New England (26 percent), the Middle Atlantic (23 percent), and the Midwest (12 percent across the West North Central and East North Central regions). Trends were also detectable in the South (9 percent across the West South Central, East South Central and the South Atlantic

Figure 4: Extreme Storms Are Happening More Frequently Across Much of the United States



The dark circles on this map represent climate divisions in which weather stations recorded an increase in the frequency of extreme storms that is unlikely to have been the result of chance, and the light circles represent areas showing a decrease. The largest increases in extreme storm frequency from 1948 to 2011 happened in New England. Substantial increases also occurred in the Mid-Atlantic, the Midwest, much of the South, and parts of the West. Climate divisions not displayed in the map either showed no trend or did not have enough data to draw a valid conclusion at this fine level of geography (79 of 344 total climate divisions).[59]

Table 2: Regional Trends in 24-Hour Total Precipitation Produced by the Largest Annual Storms at Each Weather Station

Region	Change in Total Precipitation from Largest Storms, 1948-2011	Is the Trend Significant?*
New England	26%	Yes
Middle Atlantic	23%	Yes
West North Central	12%	Yes
East South Central	11%	Yes
East North Central	10%	Yes
West South Central	9%	Yes
Mountain West	8%	Yes
South Atlantic	7%	Yes
Pacific	*2%*	*No*
OR plus CA North of San Francisco Bay	-7%	Yes
California South of San Francisco Bay	7%	Yes

regions), and the West (5 percent across the Mountain and Pacific regions). (See Table 2, or for more detail, see Table A-3 on page 36.)

At the state level, Vermont and New Hampshire experienced the largest growth in total precipitation from the biggest annual rainstorms or snowstorms, increasing 35 and 33 percent, respectively, from 1948 to 2011. Among states along the Eastern Seaboard, Massachusetts, New York, Maine, Pennsylvania, New Jersey, Connecticut and Delaware all experienced increases of 20 percent or more.

In the Midwest, Missouri experienced a 20 percent increase in total precipitation from the largest annual storms. South Dakota, Ohio, Wisconsin, Michigan, Minnesota, and Kansas all experienced growth in total precipitation from the largest annual storms of more than 10 percent. In Washington state, total precipitation from the largest storms grew by 18 percent. In the South, North Carolina (12 percent),

Figure 5: The Biggest Storms Are Getting Bigger

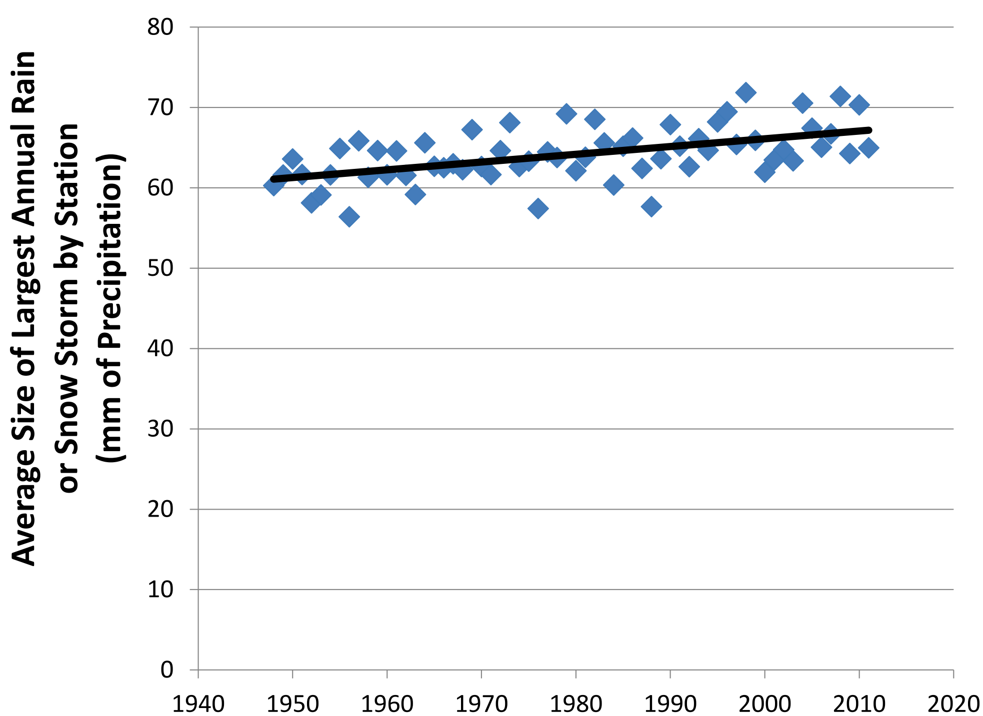
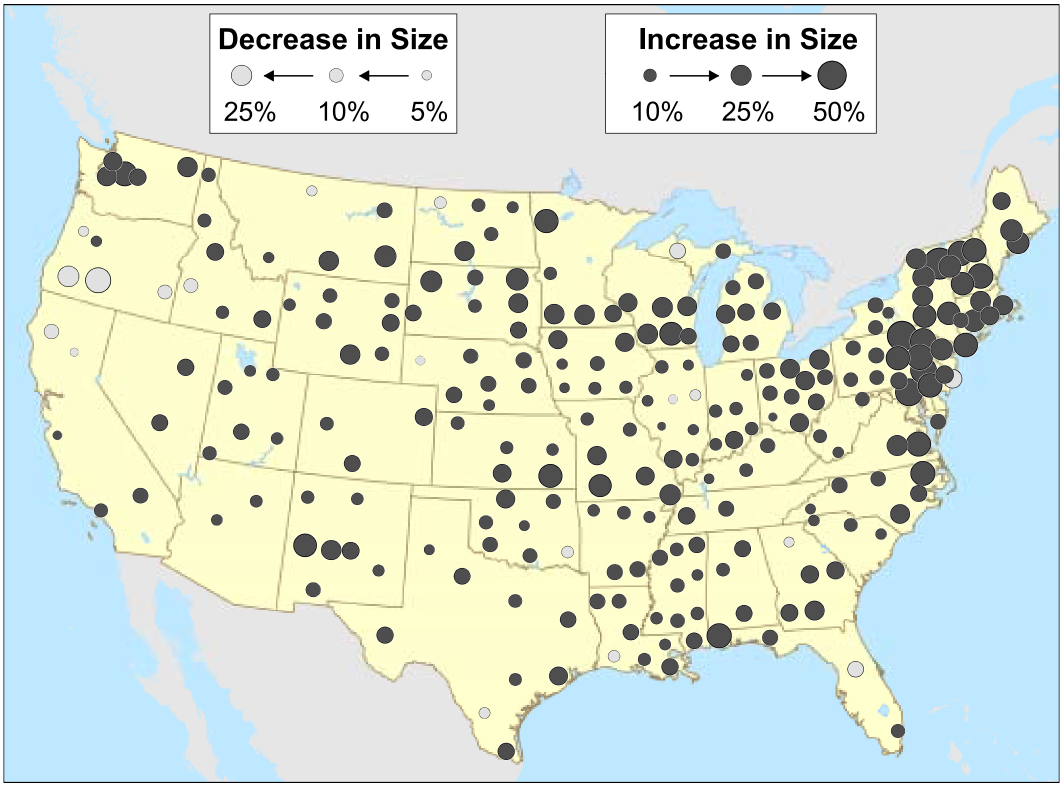


Figure 6: The Largest Annual Storms are Getting Larger Across Much of the United States



Virginia (11 percent), Mississippi (11 percent), Alabama (11 percent), and Tennessee (11 percent) all experienced increases in total rainfall from the largest annual storms greater than the national average.

In total, 43 states experienced a significant increase in total precipitation produced by the largest annual storm at each weather station. Four states—Rhode Island, Arizona, Florida and California—either did not experience a trend, or did not have enough data to draw a valid conclusion. Only one state, Oregon, showed a significant decrease. For full state data, see Table A-4 on page 36.

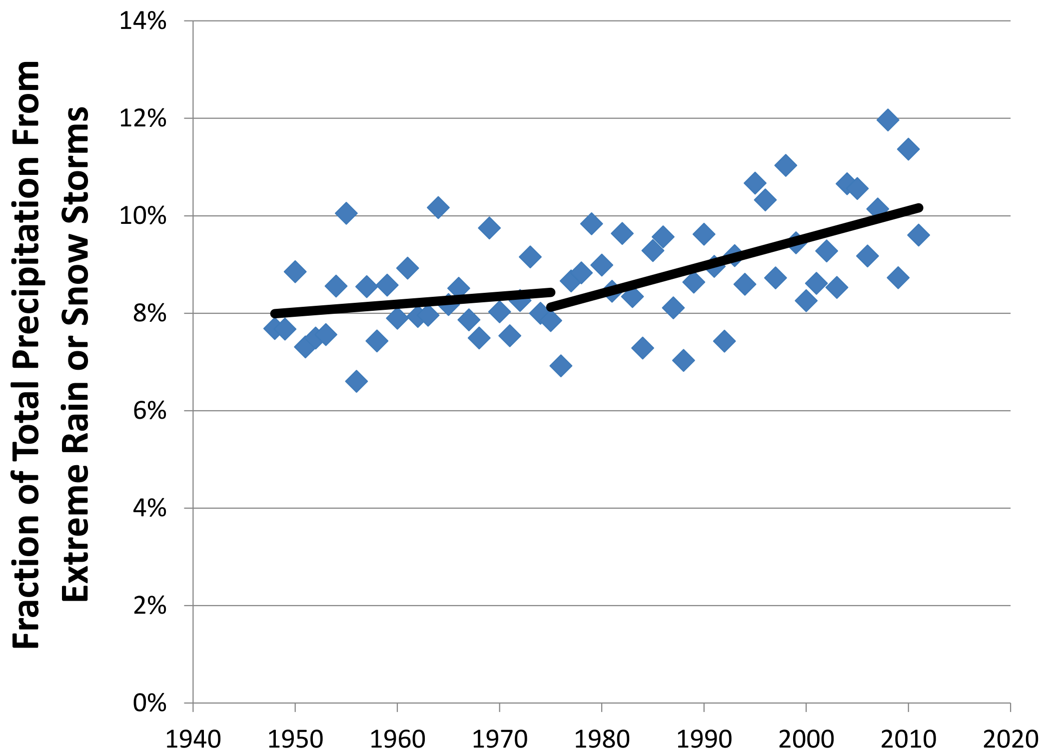
Figure 6 shows trends at the climate division level. In total, climate divisions covering 64 percent of the area of the contiguous United States showed apparent increases in the size of the largest annual storms by weather station.[60] (See the dark circles.) In contrast, apparent decreases occurred in climate divisions covering about 7 percent of national land area. (See the light circles.) The remainder of the climate divisions either did not experience a local trend, or did not have enough data to detect any local trends.

The Fraction of Annual Precipitation Coming from Extreme Downpours Has Increased

Across much of the contiguous United States, extreme storms have become more frequent. At the same time, the largest storms have grown to produce more total precipitation. As a result, extreme storms are responsible for an increasing amount of total annual rainfall or snowfall.

In1950, extreme events (those expected

Figure 7: Extreme Downpours Account for an Increasing Fraction of Total Precipitation Nationwide



to occur, on average, once per year or less at any given location) accounted for about 8 percent of total precipitation at the weather stations used for this analysis. (See Figure 7.) In the past decade, on average, extreme events produced nearly 10 percent of total precipitation at these locations. Notably, the trend appears to be relatively flat through 1975. After 1975, the slope of the trend increases four-fold. This result is consistent with work done by the U.S. Soil and Water Conservation Society in 2003 that found that "practically the entire nationwide increase in heavy and very heavy precipitation occurred [since the early 1970s]."[61]

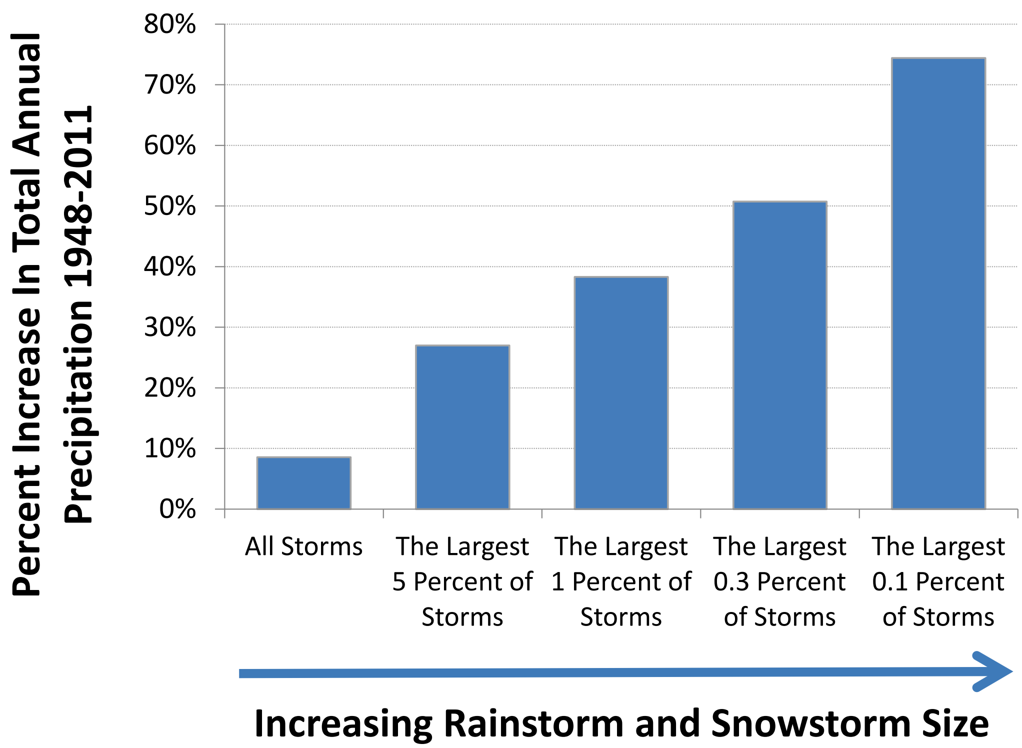
The Largest Changes Appeared at the Extremes

The trends toward more frequent and more intense rainstorms and snowstorms were even more pronounced and substantial for larger events. In other words, the most extreme storms are those that have experienced the greater increase in their likelihood.

Focusing in the most extreme rainstorms and snowstorms—those in the upper 0.3 percent to 0.1 percent of precipitation events at any given weather station over the period of analysis—shows that the more unusual the storm, the faster the increase in total precipitation over time. From 1948 to 2011,

the amount of total annual precipitation across the 3,700 weather stations scattered across the contiguous United States that were used for this analysis increased by about 9 percent. The amount of precipitation produced by the largest 5 percent of downpours at every weather station over the period of analysis increased by 27 percent. However, the amount of total annual precipitation produced by the largest 0.1 percent of downpours increased by more than 70 percent. (See Figure 8.) This is consistent with trends noted by scientists at the U.S. Soil and Water Conservation Society and the U.S. National Climatic Data Center, with trends noted by the Rocky Mountain Climate Organization and the Natural Resources Defense Council, and consistent with anticipated future impacts of global warming.[62]

Figure 8: The More Extreme the Storm, the Greater the Change

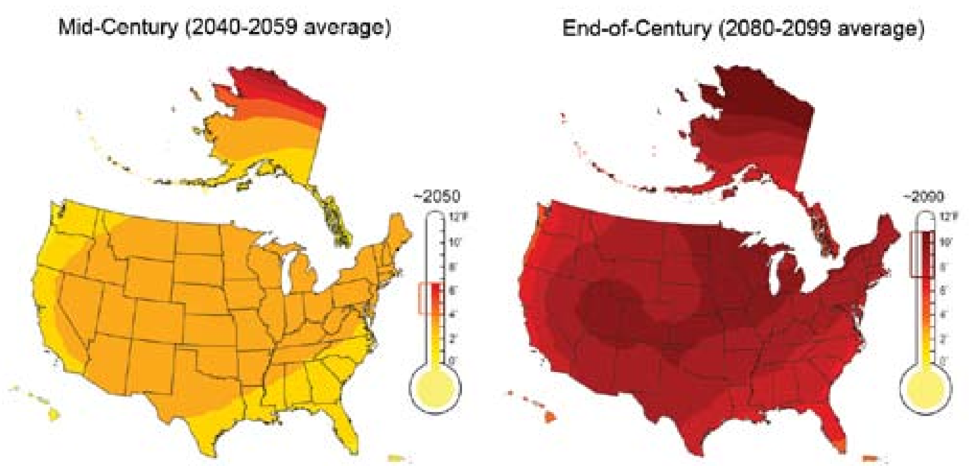


This figure shows that the very largest storms are getting bigger, faster, than other storms. All storm categories are defined relative to the local climate at each weather station used in this analysis. For example, the far right column represents the change over time in the amount of total precipitation produced by the largest 0.1 percent of storm events at each weather station we used across the contiguous United States.

Global Warming Will Very Likely Drive Future Increases in Heavy Downpours

Without significant action to reduce global warming pollution, the U.S. Global Change Research Program predicts that average temperatures in the United States could rise by as much as an additional 10° F by the end of the century.[63] (See Figure 9.) Scientists predict that this warming will further accelerate the water cycle, very likely driving additional increases in the frequency and intensity of extreme downpours while likely increasing the frequency and severity of drought at the same time.[64] These changes will very likely have a wide range of harmful consequences for the United States.

Figure 9: Projected Temperature Increase under a Scenario of High Emissions of Heat-Trapping Pollution, Relative to 1961-1979 Baseline (°F)[65]



These maps, prepared by the U.S. Global Change Research Program, present projections of future average temperature increases by mid-century and by the end of the century. The maps are based on a high-emission scenario developed by the IPCC—which on the world's current emissions trajectory, we may exceed.[66] The brackets on the thermometers represent the likely range of temperature projections.

Greater Warming Will Very Likely Make Extreme Downpours More Frequent and Intense, Increasing the Risk of Flooding

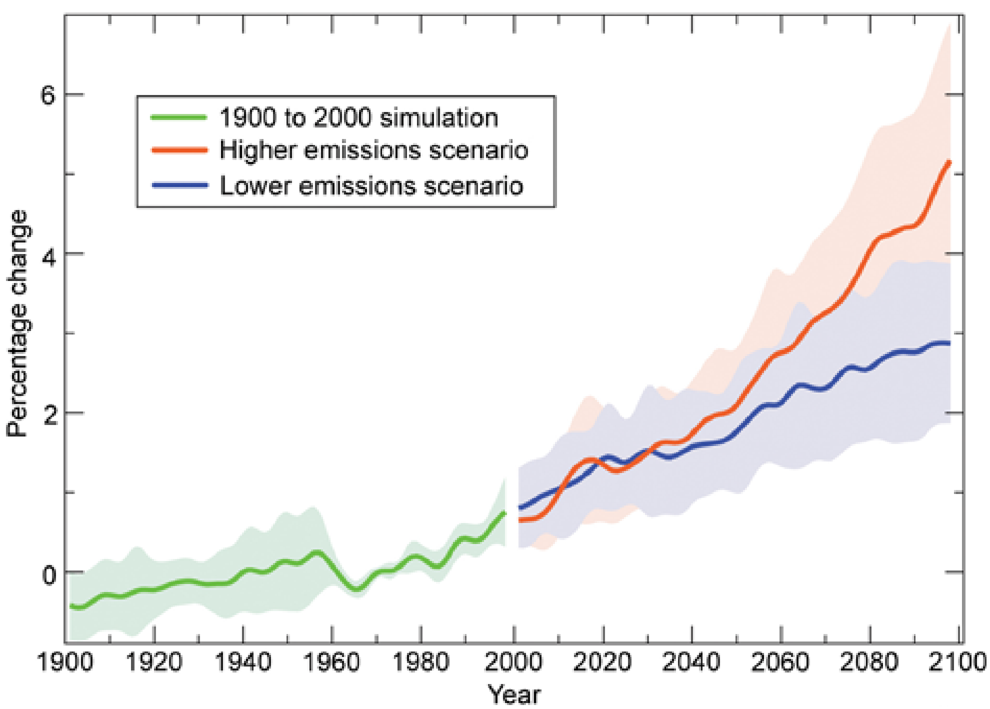
Greater warming will very likely increase the odds of storms with exceptional amounts of precipitation, increasing the risk of flooding that outstrips our ability to cope.

Experts at the U.S. Global Change Research Program predict that in the United States extreme precipitation is likely to become even more frequent and more intense. Moreover, the biggest storms are very likely to continue to get bigger, with the largest changes appearing at the extremes.[67] (See Figures 10 and 11.)

As a result, the U.S. Global Change Research Program predicts that a storm occurring once every 20 years now could occur every 4 to 15 years by the end of the century, depending on location and also on how much heat-trapping pollution we emit into the atmosphere.[68] At the same time, scientists expect heavy downpours to be 10 to 25 percent heavier, on average by the end of the century compared to now.[69]

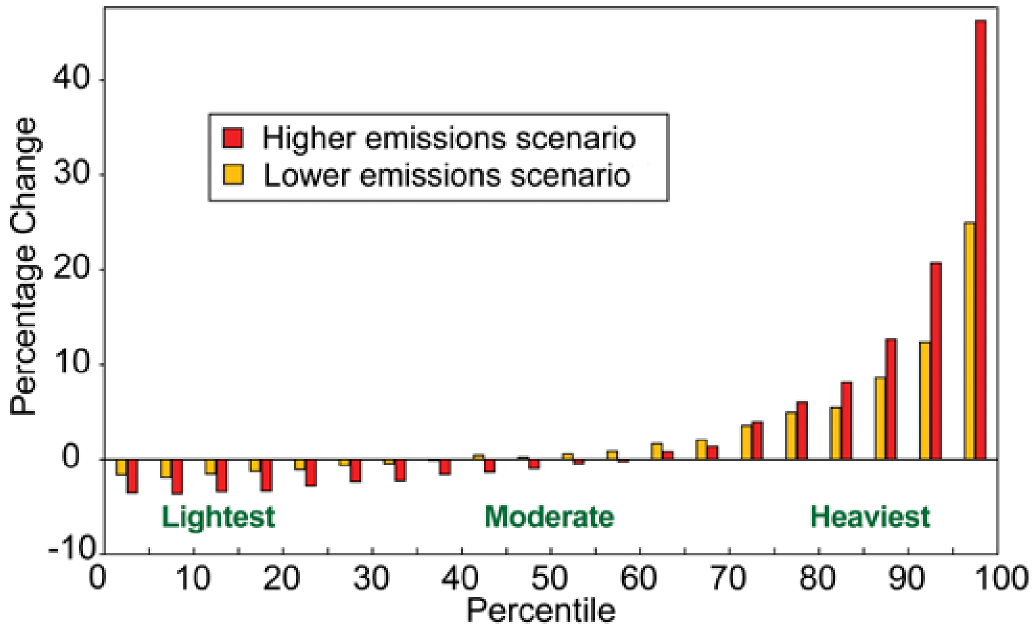
The Intergovernmental Panel on Climate Change concludes that "it is likely that the frequency of heavy precipitation … will increase in the 21st century over many

Figure 10: Global Warming Is Very Likely to Make the Heaviest Downpours More Intense[71]



This figure, produced by the U.S. Global Change Research Program, shows the projected increase in the amount of daily precipitation over the globe that falls in the heaviest 5 percent of downpours in a given year, compared to the 1960-1979 average. As a result of global warming, heavy downpours are very likely to further increase in frequency and intensity, with more emissions producing greater changes. The lines represent central projections, while the shaded areas show likely ranges. On the world's current emissions trajectory, we may exceed even the higher emissions scenario shown here.[72]

Figure 11: More Global Warming Pollution Means More Intense Downpours, with the Greatest Changes Coming at the Highest Extremes[73]



This figure, produced by the U.S. Global Change Research Program, shows projected changes from the 1990s average to the 2090s average in the amount of precipitation falling in light, moderate and heavy precipitation events in North America. The x-axis represents the spectrum of precipitation event size, with the lightest drizzles on the left and the heaviest, most unusual downpours on the right. The figure shows that the largest changes are anticipated at the highest extreme, with the heaviest downpours becoming much more intense as a result of global warming, while the lightest storms become slightly less intense. It also shows that higher emissions of global warming pollution produce larger impacts.[74]

Will Global Warming Make Future Downpours Even More Intense than Expected?

In recent years, scientists at institutions in Australia, the United States, the United Kingdom and Canada published evidence suggesting that the models of future climate change are underestimating the magnitude of future increases in precipitation intensity. Dr. Seung-Ki Min at Environment Canada and colleagues found that "changes in extreme precipitation projected by models, and thus the impacts of future changes in extreme precipitation, may be underestimated because models seem to underestimate the observed increase in heavy precipitation with warming" that has happened over the past half century.[75] Similarly, Dr. Paul Durack at the Centre for Australian Weather and Climate Research found evidence that the water cycle is becoming about 8 percent more intense for every 2° F increase in temperature, double the rate projected by most climate models.[76]

areas of the globe." In regions roughly encompassing the contiguous United States, the IPCC expresses "medium confidence" in the prediction that a storm occurring once every 20 years in the late 20th century could occur once every 5 to 15 years by the end of the 21st century.[70]

Warming Will Likely Also Increase the Frequency and Severity of Drought

Scientists predict that increasingly heavy downpours will be accompanied by an increasing risk of drought.

The increased temperatures brought by global warming will increase the rates of evaporation of moisture from the land and the ocean. This will tend to make soils dry out faster after rainfall, reducing soil moisture while simultaneously fueling potential downpours with more water vapor.

The U.S. Global Change Research Program notes that "increasing temperatures have made droughts more severe and widespread than they would have otherwise been."[78] Future temperature increases are likely to lead to more frequent and severe droughts in some regions of the United States, the already dry Southwest in particular.[79]

The Intergovernmental Panel on Climate Change projects that much of the United States could experience reduced soil moisture by the end of the century, expressing "medium confidence that droughts will intensify in the 21st century" in regions including central North America.[80]

Warmer weather will also reduce snowpack and cause spring runoff to happen earlier, increasing the risk of water shortages in late summer, especially in the West.[81]

The Hidden Cost of Building Infrastructure to Withstand Extreme Precipitation

Adoption of stronger building codes designed to ensure that buildings withstand floods, or relocation or fortification of public infrastructure such as roads and sewer systems, imposes major costs on society.

To control runoff and downstream flooding, some municipalities require new construction to be designed to accommodate runoff from a 1-year rainstorm, or a storm of a size likely to occur once per year on average based on the historical record. However, because the frequency of major storms is increasing, these developments may not function as designed. Thresholds for 1-year rainstorms were lower 40 years ago in many places than they are today — and those thresholds are likely to increase further in the future.

As a result, sewer system upgrades and construction — already expected to cost billions of dollars — are likely to be more expensive. In a March 2007 draft report, EPA estimated that increased precipitation severity in the Great Lakes region could increase the cost of design and construction of sewer systems by at least 10 percent.[77]

Society should begin planning now for a future with greater weather extremes, at the same time that we work to minimize our impact on the global climate.

Policy Recommendations: Reduce the Pollution that Causes Global Warming

Weather-related disasters—including those caused by extreme precipitation—impose massive costs on the nation and threaten the health and survival of people and treasured ecosystems. Recent scientific findings about the potential impacts of global warming on extreme weather patterns provide yet another reason for the United States and the world to take action against global warming.

Among the steps that can be taken to protect Americans from the threat of further global warming-induced extreme weather events are the following:

Federal and state governments should **adopt and implement limits on global warming pollution** capable of reducing emissions to at least 35 percent below 2005 levels by 2020 and by at least 85 percent by 2050. These emission reductions are broadly consistent with what science tells us is necessary to lessen the most costly and devastating consequences of global warming.

Strong steps to clean up existing sources of pollution should include **strong limits on the production of carbon dioxide and other pollutants**, such as the carbon pollution standards for new fossil-fired power plants proposed by the U.S. Environmental Protection Agency in March 2012.[82] The federal government should also implement and expand **fuel efficiency and carbon pollution standards for cars and light trucks** through model year 2025, as proposed by the Department of Transportation and the Environmental Protection Agency in November 2011.[83]

Additional actions should include the expansion and strengthening of carbon cap-and-trade programs such as the pioneering Regional Greenhouse Gas Initiative in the Northeast.

Federal, state and local governments should adopt and implement public policies designed to move the nation away from our dependence on fossil fuels while building momentum for future comprehensive action to curb global warming pollution. Specifically, federal, state and local governments should adopt:

- Aggressive energy efficiency standards for buildings, appliances, equipment and vehicles designed to get the most out of our current consumption of fossil fuels.

- Expanded renewable electricity standards and clean fuel standards to increase the production of clean, environmentally friendly energy in the United States.

- Increased investment in clean transportation options, such as public transportation, as well as research, development and deployment of new clean energy technologies.

Environment America Research & Policy Center's 2011 report, *The Way Forward on Global Warming*, found that these and other policies at the local, state and federal level could reduce carbon dioxide emissions from fossil fuel use in the United States to as much as 34 percent below 2005 levels—even without adoption of comprehensive climate and energy legislation in the United States Congress.

As the United States curbs emissions, we also need to **anticipate future changes in extreme weather that put the public at risk and take steps to prepare and protect our communities**. Government officials should explicitly factor the potential for global warming-induced changes in extreme weather patterns into the design of public infrastructure and revise policies that encourage construction in areas likely to be at risk of flooding in a warming climate. The nation should support the continued efforts of scientists to understand the implications of global warming and inform the public.

Methodology

The analysis of extreme precipitation frequency in this paper was based on a methodology originally developed by Kenneth Kunkel and Karen Andsager at the Illinois State Water Survey, with David Easterling at the National Climatic Data Center, published in: K. Kunkel et al., "Long-Term Trends in Extreme Precipitation Events over the Conterminous United States and Canada," *Journal of Climate* 12: 2515-2527, 1999.

Area of Study and Period of Analysis

We limited our area of study to the contiguous United States, excluding Alaska and Hawaii. We began our analysis in 1948, since weather observations in our digital weather record become increasingly scarce before this date. The period of analysis extends through the end of 2011, the most recent year with complete weather data available at the time the study was performed.

Data Source

We obtained weather data from the Global Historical Climatology Network-Daily Database maintained by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Climatic Data Center (NCDC).[84] The data provide daily records from over 75,000 stations in 180 countries and territories, including 24-hour precipitation totals, in addition to geographic coordinates for the weather stations, covering varying time periods with varying degrees of completeness. The National Climatic Data Center performs quality assurance checks on the data.

For days in which a precipitation measurement was missing, yet a measurement for snowfall was recorded (a miniscule percentage of total measurements), we filled in the missing precipitation information using the 10 to 1 ratio method (i.e., precipitation was estimated at 1/10th the amount of snowfall).[85] We discarded all observations that NCDC had flagged as having failed any type of data consistency check.

Analysis of the Trend in Extreme Precipitation Frequency

We analyzed data from stations that were missing fewer than 10 percent of observations during the period of analysis. We were left with precipitation records from

3,743 weather stations in 48 states. Figure 12 shows the locations of these stations.

Definition of Extreme Precipitation

We identified storms with extreme levels of precipitation relative to the local climate at each individual weather station. We chose to examine the frequency of 24-hour precipitation events with total precipitation magnitude with a 1-year recurrence interval or larger. In other words, for a given weather station, we identified the 64 largest 1-day precipitation totals during the 64-year period of analysis. We defined these storms at each given weather station as extreme. Figure 13 graphically presents the minimum thresholds yielded by this procedure to define extreme precipitation relative to the local climate, with values between weather stations calculated by interpolation.

Analysis of Extreme Precipitation Frequency

For each weather station, we calculated the annual frequency of storms with extreme levels of precipitation. The average for each weather station over the period of analysis was 1. If no change had occurred in the frequency of extreme downpours, we would expect the trend in annual major storm frequency over time to be close to zero. A significant positive or negative slope would indicate a change in the annual frequency of major storms over time.

To calculate the trend in major storm events per station over time, we aggregated data based on station location: for the United States as a whole; by the nine census divisions;[86] by state; and by climate division.[87] We then tested for the presence of a trend using standard least-squares regression, calculating both a slope and

Figure 12: Location of Weather Stations Used in the Analysis

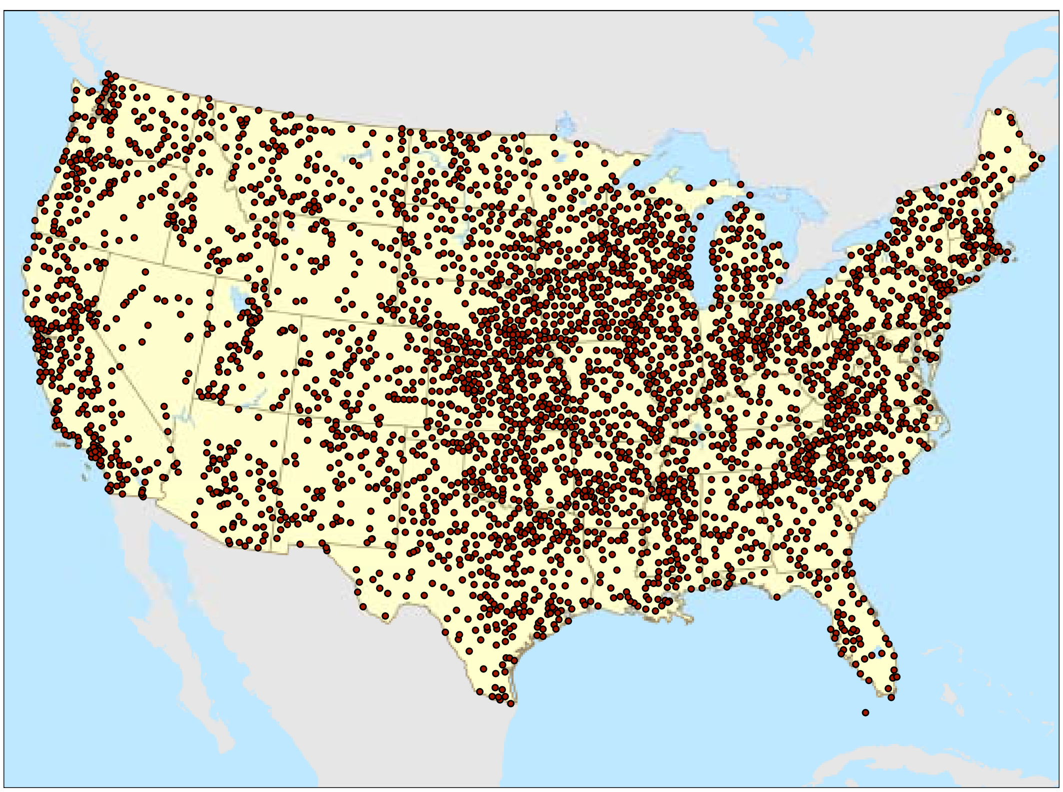
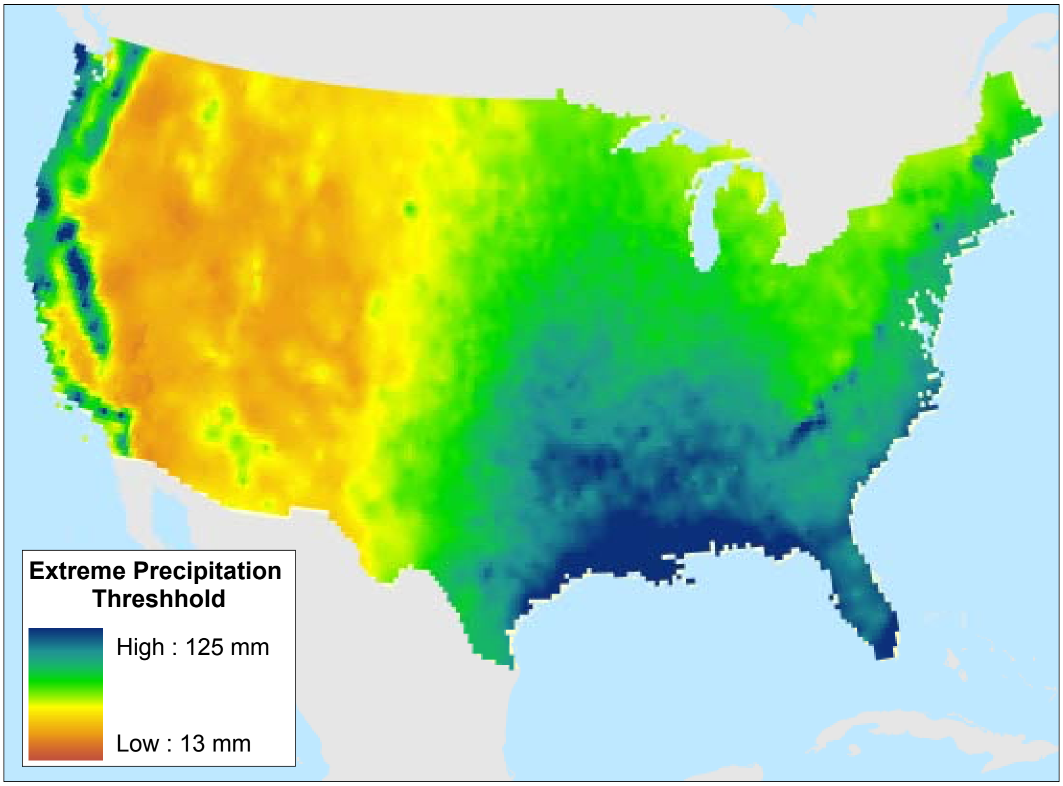


Figure 13: Minimum 24-Hour Precipitation Thresholds for the Definition of Extreme Precipitation Across the Contiguous United States



its standard error. We then calculated the percentage probability that the slope differed from zero to determine the statistical significance of any resulting trends.

Analysis of Extreme Precipitation Size

We also analyzed trends in the total amount of precipitation delivered by the largest rainstorm or snowstorm in each year at each weather station. For this analysis, we selected the single largest storm at each weather station in each year, and then calculated the trend in the total amount of rainfall or snowfall delivered by these storms over time. This analysis eliminates the influence of any increase in heavy downpour frequency and isolates trends in the amount of precipitation produced by the largest storms. We aggregated data based on station location: for the United States as a whole; by the nine census divisions;[88] by state, and by climate division.[89]

We examined trends over time using standard least-squares regression, calculating both a slope and its standard error. We then calculated the percentage probability that the slope differed from zero to determine the statistical significance of any resulting trends.

Nationally, we also investigated whether the trend in the total annual amount of precipitation delivered by extreme events was different at different definitions of "extreme" precipitation. These additional definitions of "extreme" were based on event frequency at each weather station, looking at the top 5 percent of precipitation events at each weather station; the top 1 percent of events; the top 0.3 percent of events and the top 0.1 percent of events.

Appendix

Table A-1: Regional-Level Increase in Extreme Precipitation Frequency, 1948-2011

Region	Increase in Extreme Precipitaton Frequency, 1948-2011	95 Percent Confidence Interval	A Storm That Used to Occur Every 12 Months Now Occurs on Average Every:	95 Percent Confidence Interval	Probability that the Trend Differs from Zero	Statistically Significant?
New England	85%	76% - 94%	6.5 months	6.2 - 6.8 months	100%	Yes
Middle Atlantic	55%	49% - 62%	7.7 months	7.4 - 8.1 months	100%	Yes
West North Central	36%	33% - 39%	8.8 months	8.6 - 9.0 months	100%	Yes
East North Central	34%	30% - 38%	9.0 months	8.7 - 9.2 months	100%	Yes
West South Central	31%	28% - 35%	9.1 months	8.9 - 9.4 months	100%	Yes
East South Central	30%	24% - 36%	9.2 months	8.8 - 9.6 months	100%	Yes
Mountain	26%	22% - 30%	9.5 months	9.3 - 9.8 months	100%	Yes
South Atlantic	17%	12% - 21%	10.3 months	9.9 - 10.7 months	100%	Yes
Pacific	6%	2% - 11%	11.3 months	10.8 - 11.8 months	99%	Yes
Oregon plus California North of San Francisco Bay	-25%	-32% - -18%	16.0 months	14.6 - 17.7 months	100%	Yes
California South of San Francisco Bay	35%	26% - 43%	8.9 months	8.4 - 9.5 months	100%	Yes

Table A-2: State-Level Increase in Extreme Precipitation Frequency, 1948-2011

Rows in italics indicate results that are not statistically significant.

State	Increase in Extreme Precipitaton Frequency, 1948-2011	95 Percent Confidence Interval	A Storm That Used to Occur Every 12 Months Now Occurs on Average Every:	95 Percent Confidence Interval	Probability that the Trend Differs from Zero	Statistically Significant?
ALABAMA	41%	28% - 54%	8.5 months	7.8 - 9.4 months	100%	Yes
ARKANSAS	34%	25% - 43%	8.9 months	8.4 - 9.6 months	100%	Yes
ARIZONA	24%	13% - 35%	9.7 months	8.9 - 10.6 months	100%	Yes
CALIFORNIA	13%	6% - 19%	10.7 months	10.1 - 11.3 months	100%	Yes
COLORADO	25%	15% - 34%	9.6 months	8.9 - 10.4 months	100%	Yes
CONNECTICUT	73%	47% - 99%	6.9 months	6.0 - 8.2 months	100%	Yes
DELAWARE	*30%*	*-12% - 72%*	*9.2 months*	*7.0 - 13.6 months*	*84%*	*No*
FLORIDA	*-1%*	*-12% - 11%*	*12.1 months*	*10.8 - 13.6 months*	*10%*	*No*
GEORGIA	13%	3% - 24%	10.6 months	9.7 - 11.7 months	99%	Yes
IOWA	35%	27% - 42%	8.9 months	8.4 - 9.5 months	100%	Yes
IDAHO	14%	3% - 26%	10.5 months	9.5 - 11.7 months	98%	Yes
ILLINOIS	16%	7% - 24%	10.4 months	9.7 - 11.2 months	100%	Yes

Table A-2: Continued

State	Increase in Extreme Precipitaton Frequency, 1948-2011	95 Percent Confidence Interval	A Storm That Used to Occur Every 12 Months Now Occurs on Average Every:	95 Percent Confidence Interval	Probability that the Trend Differs from Zero	Statistically Significant?
INDIANA	32%	21% - 43%	9.1 months	8.4 - 9.9 months	100%	Yes
KANSAS	35%	28% - 41%	8.9 months	8.5 - 9.4 months	100%	Yes
KENTUCKY	35%	21% - 49%	8.9 months	8.0 - 9.9 months	100%	Yes
LOUISIANA	41%	28% - 54%	8.5 months	7.8 - 9.4 months	100%	Yes
MASSACHUSETTS	81%	64% - 99%	6.6 months	6.0 - 7.3 months	100%	Yes
MARYLAND	*18%*	*-3% - 40%*	*10.1 months*	*8.6 - 12.3 months*	*91%*	*No*
MAINE	74%	56% - 93%	6.9 months	6.2 - 7.7 months	100%	Yes
MICHIGAN	37%	27% - 47%	8.8 months	8.2 - 9.4 months	100%	Yes
MINNESOTA	30%	21% - 39%	9.2 months	8.6 - 9.9 months	100%	Yes
MISSOURI	53%	43% - 62%	7.9 months	7.4 - 8.4 months	100%	Yes
MISSISSIPPI	22%	13% - 32%	9.8 months	9.1 - 10.6 months	100%	Yes
MONTANA	17%	9% - 25%	10.3 months	9.6 - 11.0 months	100%	Yes
NORTH CAROLINA	20%	11% - 29%	10.0 months	9.3 - 10.8 months	100%	Yes
NORTH DAKOTA	33%	24% - 43%	9.0 months	8.4 - 9.7 months	100%	Yes
NEBRASKA	30%	23% - 37%	9.2 months	8.8 - 9.8 months	100%	Yes
NEW HAMPSHIRE	115%	94% - 137%	5.6 months	5.1 - 6.2 months	100%	Yes
NEW JERSEY	33%	14% - 51%	9.1 months	7.9 - 10.5 months	100%	Yes
NEW MEXICO	36%	27% - 44%	8.9 months	8.3 - 9.5 months	100%	Yes
NEVADA	27%	10% - 45%	9.4 months	8.3 - 10.9 months	100%	Yes
NEW YORK	64%	55% - 73%	7.3 months	6.9 - 7.8 months	100%	Yes
OHIO	49%	40% - 58%	8.1 months	7.6 - 8.6 months	100%	Yes
OKLAHOMA	32%	24% - 40%	9.1 months	8.6 - 9.7 months	100%	Yes
OREGON	-24%	-33% - -14%	15.7 months	14.0 - 17.9 months	100%	Yes
PENNSYLVANIA	52%	41% - 62%	7.9 months	7.4 - 8.5 months	100%	Yes
RHODE ISLAND	90%	29% - 152%	6.3 months	4.8 - 9.3 months	100%	Yes
SOUTH CAROLINA	*-1%*	*-13% - 11%*	*12.1 months*	*10.8 - 13.8 months*	*13%*	*No*
SOUTH DAKOTA	45%	36% - 54%	8.3 months	7.8 - 8.9 months	100%	Yes
TENNESSEE	30%	18% - 42%	9.2 months	8.4 - 10.2 months	100%	Yes
TEXAS	29%	23% - 34%	9.3 months	9.0 - 9.7 months	100%	Yes
UTAH	37%	27% - 48%	8.7 months	8.1 - 9.5 months	100%	Yes
VIRGINIA	33%	23% - 44%	9.0 months	8.4 - 9.8 months	100%	Yes
VERMONT	84%	62% - 106%	6.5 months	5.8 - 7.4 months	100%	Yes
WASHINGTON	24%	13% - 34%	9.7 months	9.0 - 10.6 months	100%	Yes
WISCONSIN	38%	31% - 46%	8.7 months	8.2 - 9.2 months	100%	Yes
WEST VIRGINIA	34%	21% - 47%	8.9 months	8.1 - 9.9 months	100%	Yes
WYOMING	32%	20% - 44%	9.1 months	8.3 - 10.0 months	100%	Yes

Table A-3: Regional-Level Increase in 24-Hour Total Precipitation Produced by the Largest Annual Rainstorm or Snowstorm at Each Weather Station, 1948-2011

Rows in italics indicate results that are not statistically significant.

Region	Increase in Size of the Largest Annual Storm by Station, 1948-2011	Percent Confidence 95 Interval	Probability that the Trend Differs from Zero	Statistically Significant?
New England	26%	22% - 30%	100%	Yes
Middle Atlantic	23%	20% - 26%	100%	Yes
West North Central	12%	11% - 14%	100%	Yes
East South Central	11%	8% - 13%	100%	Yes
East North Central	10%	9% - 12%	100%	Yes
West South Central	9%	7% - 11%	100%	Yes
Mountain	8%	7% - 10%	100%	Yes
South Atlantic	7%	6% - 9%	100%	Yes
Pacific	*2%*	*-1% - 5%*	*80%*	*No*
Oregon plus California North of San Francisco Bay	-7%	-11%- -3%	100%	Yes
California South of San Francisco Bay	7%	2% - 13%	99%	Yes

Table A-4: State-Level Increase in 24-Hour Total Precipitation Produced by the Largest Annual Rainstorm or Snowstorm at Each Weather Station, 1948-2011

Rows in italics indicate results that are not statistically significant.

State	Increase in Size of the Largest Annual Storm by Station, 1948-2011	Percent Confidence 95 Interval	Probability that the Trend Differs from Zero	Statistically Significant?
ALABAMA	11%	6% - 16%	100%	Yes
ARKANSAS	6%	3% - 9%	100%	Yes
ARIZONA	*4%*	*0% - 9%*	*93%*	*No*
CALIFORNIA	*1%*	*-3% - 5%*	*40%*	*No*
COLORADO	8%	4% - 13%	100%	Yes
CONNECTICUT	20%	8% - 32%	100%	Yes
DELAWARE	20%	1% - 38%	96%	Yes
FLORIDA	*1%*	*-3% - 6%*	*44%*	*No*
GEORGIA	6%	2% - 10%	100%	Yes
IOWA	10%	7% - 13%	100%	Yes
IDAHO	7%	2% - 12%	99%	Yes
ILLINOIS	5%	2% - 8%	100%	Yes

Table A-4: Continued

State	Increase in Size of the Largest Annual Storm by Station, 1948-2011	Percent Confidence 95 Interval	Probability that the Trend Differs from Zero	Statistically Significant?
INDIANA	8%	4% - 12%	100%	Yes
KANSAS	12%	9% - 15%	100%	Yes
KENTUCKY	10%	5% - 15%	100%	Yes
LOUISIANA	10%	5% - 15%	100%	Yes
MASSACHUSETTS	25%	18% - 33%	100%	Yes
MARYLAND	14%	5% - 24%	100%	Yes
MAINE	23%	16% - 30%	100%	Yes
MICHIGAN	12%	9% - 16%	100%	Yes
MINNESOTA	12%	8% - 16%	100%	Yes
MISSOURI	20%	16% - 23%	100%	Yes
MISSISSIPPI	11%	7% - 14%	100%	Yes
MONTANA	8%	5% - 12%	100%	Yes
NORTH CAROLINA	12%	9% - 16%	100%	Yes
NORTH DAKOTA	6%	1% - 10%	99%	Yes
NEBRASKA	9%	6% - 12%	100%	Yes
NEW HAMPSHIRE	33%	22% - 43%	100%	Yes
NEW JERSEY	22%	14% - 30%	100%	Yes
NEW MEXICO	10%	6% - 15%	100%	Yes
NEVADA	9%	0% - 17%	96%	Yes
NEW YORK	25%	20% - 29%	100%	Yes
OHIO	15%	12% - 18%	100%	Yes
OKLAHOMA	9%	5% - 12%	100%	Yes
OREGON	-7%	-12% - -2%	99%	Yes
PENNSYLVANIA	23%	18% - 27%	100%	Yes
RHODE ISLAND	*20%*	*-2% - 43%*	*92%*	*No*
SOUTH CAROLINA	4%	0% - 9%	95%	Yes
SOUTH DAKOTA	17%	13% - 21%	100%	Yes
TENNESSE	11%	7% - 15%	100%	Yes
TEXAS	10%	7% - 13%	100%	Yes
UTAH	10%	5% - 15%	100%	Yes
VIRGINIA	11%	7% - 16%	100%	Yes
VERMONT	35%	26% - 43%	100%	Yes
WASHINGTON	18%	11% - 24%	100%	Yes
WISCONSIN	13%	10% - 16%	100%	Yes
WEST VIRGINIA	6%	2% - 10%	100%	Yes
WYOMING	11%	5% - 17%	100%	Yes

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